Application of Open Pore Cellular Foam for Air Breathing PEM Fuel Cell

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Abstract

Open Pore Cellular Foam (OPCF) has received increased attention for use in Proton Exchange Membrane (PEM) fuel cells as a flow plate due to some advantages offered by the material, including better gas flow, lower pressure drop and low electrical resistance.

In the present study, a novel design for an air-breathing PEM (ABPEM) fuel cell, which allows air convection from the surrounding atmosphere, using OPCF as a flow distributor has been developed. The developed fuel cell has been compared with one that uses a normal serpentine flow plate, demonstrating better performance.

A comparative analysis of the performance of an ABPEM and pressurised air PEM (PAPEM) fuel cell is conducted and poor water management behaviour was observed for the ABPEM design.

Thereafter, a PTFE coating has been applied to the OPCF with contact angle and electrochemical polarisation tests conducted to assess the capability of the coating to enhance the hydrophobicity and corrosion protection of metallic OPCF in the PEM fuel cell environment. The results showed that the ABPEM fuel cell with PTFE coated OPCF had a better performance than that with uncoated OPCF.

Finally, OPCF was employed to build an ABPEM fuel cell stack where the performance, advantages and limitations of this stack are discussed in this paper.

Keywords: PEM, Fuel Cell, Open Pore Cellular Foam, Flow Plate, Air-breathing

1. Introduction

With the new EU strategy for the future energy market that aim to cover the full energy demands of the zone through renewable and sustainable energy systems, a considerable amount of research work has been directed toward developing innovative renewable and clean energy systems that can help achieving the 100% renewable energy target [1].

Among the various energy systems, Proton Exchange Membrane (PEM) fuel cells were identified as promising power sources for a variety of portable and stationary power applications [2]–[5]. PEM fuel cells use a solid polymer in the form of a solid phase proton conducting membrane as an electrolyte. They have many advantages over the other fuel cell types; including low temperature operation, high power density, fast start up, system robustness, flexibility of fuel type (with reformer) and reduced sealing, corrosion, shielding or leaking concerns [6]. A PEM fuel cell consists of a Membrane Electrode Assembly (MEA), which contains a proton exchange membrane, an electrically conductive porous Gas Diffusion Layer (GDL) and an electro-catalyst layer, sandwiched between two gas distribution flow plates which distribute the fuel and oxidant to the reactive sites of the MEA.

The PEM fuel can be configured with a forced convection cathode design for active supply of oxygen from pressurised air or by passively taking in the oxygen from the atmosphere in an air-breathing design [7]. In case of oxygen active supply PEM fuel cells, or Pressurised Air PEM (PAPEM) fuel cell, the air or oxygen is supplied to the cathode by forced convection through appropriately designed flow passages. The Air-Breathing PEM (ABPEM) fuel cells have their cathode structures open to air so oxygen can be absorbed passively through free convection from its surroundings. ABPEM fuel cells have provided significant advantages in portable power source over PAPEM fuel cells and battery systems [8]. They do not require moving parts, such as external humidification instruments, fans or pumps, for operating and thus they can be made very compact and simple with very low parasitic losses.

Generally, ABPEM fuel cells are characterised by low output power densities compared to PAPEM fuel cells. The maximum power density of an ABPEM fuel cell is around 350 mW/cm^2 while the PAPEM fuel cell has a power density in the range of 566 mW/cm^2 [9]. The performance of ABPEM fuel cell depends on the amount and characteristics of the surrounding air including humidity and temperature. Thus the design of an ABPEM fuel cell requires special care as so to allow sufficient air reaching the cathode [10]. The generated water in ABPEM cannot be removed easily by the free convection of the air. This results in clogging the pores of the GDL on the cathode side by the generated water, thus preventing air from being sufficiently fed to the cell [11].

One of the key strategies for improving the performance of the PEM fuel cell is the effective design of the Bipolar plate (BPs). BP performs vital roles, such as distributing the fuel and

oxidant to the catalyst layer, removing the water from the fuel cell and collecting the produced current, that are essential for an effective performance of the system [12], [13]. The BP can be configured with various designs of flow channels such as straight parallel channels, serpentine channels, integrated channels, interdigitated channels and bio-inspired flow fields [14]. The channels-based bipolar plates have common drawbacks such as; large pressure losses, high cost of manufacturing and low mechanical strength; which increase the weight and volume of the fuel cell. In addition, the flow channels can cause unequal distribution of the electrochemical reactions which lead to irregular utilisation of the catalyst [15]. As an alternative to channels-based BP, Open Pore Cellular Foam (OPCF) metallic materials was used as bipolar plates and exhibited several key advantages such as better gas flow through the fuel cell, lower pressure drop from inlet to outlet and lower manufacturing cost [15]–[21].

However, metallic materials, such as OPCF, considered for bipolar applications are prone to corrosion and exhibit high contact resistance in PEM fuel cell environments (pH=2-3 at ~ 70°C) [22]. To overcome the corrosion and high ICR problems, significant research work have been directed into improving the corrosion resistance via surface modifications. Among the various types of coating, polytetrafluoroethylene (PTFE) composite coating was considered as a suitable option for PEM application due to its potentials to improve the hydrophilicity of the bipolar plates that in turn allows for better water management and reduce the mass transport loses of the PEM fuel cell [23]–[25].

Despite the advantages of OPCF flow plate material, particularly those with PTFE coating, it has received little application for air-breathing PEM fuel cell designs. Thus, in this paper, innovative designs of Air-Breathing PEM (ABPEM) single fuel cell and a stack with four cells were developed using OPCF flow plates. The fuel cells performances were investigated experimentally and the results identified the main advantages and problems of the design. Various solutions were suggested to overcome the limitations of the design and the feasibility of each solution was discussed.

2. Experiments

2.1 Fuel cell material and fabrication

In this study, three different designs of the PEM fuel cell were developed. The first fuel cell type is Air Breathing PEM (ABPEM) fuel cell in which air is absorbed passively through free convection from the surrounding atmosphere, as shown in Figure 1. The second fuel cell design is Pressurised Air PEM (PAPEM) in which air is supplied with forced convection to the cathode side. The final design is the air-breathing fuel cell stack, Figure 2, which was constructed using four PEM fuel cells based on Patent US9444117 B2 [26]. The main advantage of the current stack design is that it only use two anode sides, i.e. two OPCF with hydrogen supply, to generate 4 cells while the conventional stack design require 4 anode sides to create such a stack. It contains two outer and three internal OPCFs. Each internal OPCF in the stack provide either hydrogen or air to the adjacent MEAs on left and right sides. This design can significantly reduce the size, complexity and cost of the stack.

An OPCF plate was used as flow distributor on both anode and cathode sides. The OPCF on the anode side is supplied with hydrogen through appropriate gas connectors.

Silicon gaskets were used for gas sealing of both anode and cathode. Nafion 212 with an active area of 25 cm^2 was used as membrane electrode assembly. Aluminium end plates were used to provide the required uniform pressure over the flow plates. Table 1 summarises the material properties of the fuel cell components used in this study. All components are assembled together using bolts with nuts. The use of metal foam eliminated the need for some supplementary components such as current collectors which are used with the conventional flow plate.

2.2 Fuel cell polarisation testing

The experimental setup is similar to Carton and Olabi [13], as shown in Figure 3. The reactant gas, hydrogen, is stored in a compressed cylinder. Pressure regulators manage the hydrogen and air pressure, while volumetric flow meters (calibrated for the hydrogen gas and air) control the mass flow. The flow controllers are controlled by the data acquisition (DAQ) software (Lab View). The fuel cell open circuit voltage, operating voltage and current were measured by a Gamry Interface 1000 (Scientific & Medical Products Limited, UK) potentiostat. The open circuit voltage and current readings are also checked at the anode and cathode using a multimeter (Fluke 8808A digital multimeter).

Every effort was made to keep parameters constant during the experiments to ensure that the values of resistance, pressure and flow were not changed from one experiment to the next. These parameters were checked throughout the experiment to identify any unwanted errors.

2.3 Surface and coating characterisation

A PTFE coating was applied to OPCF on the anode and cathode sides of the ABPEM fuel cell at ambient temperature and pressure using a technique known as CoBlast^{TM}.

Prior to deposition, the various substrates were thoroughly washed with isopropanol, air dried and arranged on the platform of the CoBlast^{TM} coating equipment at a working distance of 20 mm from the CoBlast^{TM} nozzle head. The metal surfaces were thereafter modified by blasting with streams of the processed powder fed through the CoBlast^{TM} nozzle at 90 psi and speed of 12 mm/s [27]. The blasting process was continued in the perpendicular direction until the entire surface was covered. After coating, the modified surfaces were blasted with dry air to remove loosely adhered material and washed with isopropanol.

Surface morphologies of the samples were examined with a bench top ZEISS EVOLS 15 SEM operated at 15kV accelerating voltage in the secondary and backscattered electron mode while compositional analysis of the samples was obtained using EDX (INCA, Oxford instruments).

Water contact angle measurements were conducted with a FTA200 (First Ten Angstroms, Portsmouth, USA) contact angle analyser. A predefined volume of distilled water was dropped on the surfaces of the sample via a computer controlled syringe pump. Images of the water drop on the surface of the samples were captured and then analysed with the FTA32 Video 2.0 software. Mean values for three measurements are reported.

The electrochemical test setup used for evaluating the corrosion behaviour of the samples consisted of a flat corrosion cell (Princeton Applied Research, K0235, USA) in which the working electrode (coated and uncoated metal samples) are pressed against a Teflon “O” ring exposing 1 cm^2 of the working electrode to the electrolyte, 0.5M H_2SO_4 + 2ppm HF with an Ag/AgCl (saturated KCl) as the reference electrode and a platinum mesh as the counter electrode. The setup was connected to a Gamry Interface 1000 (Scientific & Medical Products Limited, UK) potentiostat. Potentiodynamic scans were conducted at 70° C. Potentiodynamic scans were conducted at a scan rate of 1 mV/s from −1 V vs.OCP to 1 V vs. reference while the open circuit potential (OCP) was measured for 15 minutes.

3. Results and Discussion

3.1 Advantage of using OPCF for ABPEM fuel cells

In order to explain the advantage of using OPCF for ABPEM fuel cell, the performance of ABPEM that uses OPCF as flow distributor were compared against the performance of traditional ABPEM that studied by Jeong et al [28], as shown in Figure 4.

Jeong et al [28] conducted an experimental investigation into the effects of cathode open area and relative humidity on the performance of ABPEM fuel cell. A graphite flow field with five-serpentine channels was used for hydrogen delivery on the anode side. Their results showed that the fuel cell with open area of 77% exhibited the highest performance. The results used in the comparison are for the cell with open area of 77% and humidity of 80 % (the same humidity recorded during our tests).

Upon examination of Figure 4, it can be seen that both cells exhibit similar performance at low current densities (below 0.25 A/cm^2). As the current density increased above 0.25 A/cm^2, the OPCF flow plate outperforms the graphite one where the voltage and power density of conventional fuel cell dropped considerably. This is attributed to fact that using OPCF plate on the anode side allows for better distribution and uniformity of hydrogen over the catalyst layers. Additionally, using of OPCF plate as current collector on the cathode side in the ABPEM fuel cell seems to help in removing the generated water and improving the water management of the cell.

3.2 Performance comparison of ABPEM and PAPEM fuel cells

Figure 5 represents I–V curves for the single fuel cells with air-breathing and pressurized air cathode designs. A value of 0.86V was recorded for the open circuit voltage (OCV) in PAPEM fuel cell. This value is higher than that recorded in case of the ABPEM fuel cell, which is 0.79V. This may be due to the low concentration of the oxygen available in the case of air-breathing fuel cell which absorbs the air from the atmosphere through free convection. When the current density increased, it was noticed that the ABPEM fuel cell has higher losses compared with the PAPEM fuel cell. The voltage dropped from 0.79 to 0.51V when the current density increased from 0 to 0.02 A cm^{-2}, which represents 0.28V loss. While, a value of 0.24 V has been recorded as a voltage loss in case of PAPEM fuel cell. The higher losses in the ABPEM may be due to severe mass transport limitations, where the produced water in the ABPEM fuel cell is not easily removed by the natural convection of the air. This can

result in the mass transport through pores in the catalyst layer and the gas diffusion media to be inhibited by residual produced water.

Oxidant humidity could be another reason for the lower performance of ABPEM fuel cell. During the tests, the humidity of the air supplied to the PAPEM fuel cell was between 90-95 % while the humidity of the air at the room temperature was around 70-80 %. The higher humidity, in case of PAPEM, makes the ionic conductivity of the electrolyte membrane higher and it results in higher electrochemical active surface area [28].

3.3 Performance of ABPEM fuel cell assisted with a fan

One possible reason for the lower performance of ABPEM fuel cell, as stated in section 3.2, is the low concentration of oxygen available in air surrounding the ABPEM fuel cell. Therefore, a fan has been used to assist the ABPEM fuel cell and to serve two main aims; first to increase the air flow through the cell; and second to remove the excess produced water from the cell. A performance comparison of ABPEM fuel cell with and without fan is shown in Figure 6.

In an unexpected manner, the ABPEM fuel cell assisted by the fan performed less than that without the fan. This could be due to the fact that high air flow, generated when using the fan, potentially drying the membrane and causing ionic conductivity of the electrolyte membrane to be reduced.

3.4 Performance of ABPEM fuel cell with PTFE coated OPCF

It was identified in section 3.1 that the main challenge behind the lower performance of ABPEM fuel cell compared to PAPEM fuel cell is the poor water management of ABPEM. It is believed that modifying the surface of OPCF by using PTFE coating could help in this issue due to the fact that the PTFE coating can improve the hydrophobicity of OPCF and thus it could contribute to better water management in the fuel cell. Additionally, PTFE coating can also enhance the corrosion resistance of OPCF in the PEM fuel cell environment and enable greater electric output.

To prove the potential advantages of the applying PTFE coating, an ex-stiu evaluation of the PTFE coated OPCF was first conducted first.

The surface morphologies of uncoated and coated of OPCF are displayed in Figure 7 indicating a good coverage of the PTFE coating.

Figure 8 shows photographs of a water droplet on the surfaces of coated and uncoated OPCF along with the mean value of contact angles with water (φ). The contact angles are 118.7^{o},

131.05^{o} for uncoated and PTFE-coated OPCF, respectively. It is clear that the contact angle of the PTFE-coated OPCF is higher than the uncoated sample. This is a proof that the PTFE-coated OPCF has an improved hydrophobic characteristic which should allow for better water management inside the ABPEM fuel cell.

Figure 9 displays the potentiodynamic polarisation curve for the coated OPCF and bare OPCF in simulated PEM fuel environment of 0.5M H_2SO_4 + 2ppm HF at 70°C. It can be seen that the PTFE coated OPCF sample exhibited higher corrosion potentials (E_{corr}) and smaller corrosion current density (I_{corr}). This confirms the capability of PTFE coating to improve the corrosion protection of OPCF in the simulated PEM fuel cell environment.

The results of an in-stiu evaluation of the PTFE coated OPCF, which was completed using a small fuel cell with an active area of 5 cm^2, are presented in Figure 10. The fuel cell assembled with coated OPCF performs better than that with uncoated OPCF. It seems that the PTFE coated OPCF help improving the performance of ABPEM fuel cell particularly at high current densities values where the water management issue becomes more obvious. However, at low current densities, the coated OPCF fuel cell exhibited lower performance than uncoated OPCF and this could be attributed to the higher interfacial contact resistance induced by using uncoductive PTFE coating on metallic surfaces [24].

3.5 Performance of ABPEM Fuel Cell Stack

Due to the design of the stack, as detailed in section 2.1, each cell could be tested individually. This allowed evaluating the performance of individual cells within the stack, as well as the complete stack. The polarisation curves of each cell in the stack are shown in Figure 11. It can be seen that all the individual cells did not perform equally. This may be due to differences in the MEA or water build up in the cells. Cell1 outperforms the other cells, producing 0.2 A cm^{-2} at 0.6V, and this could be attributed to the stack design that contains only one port for hydrogen supply from the side adjacent to cell1, as seen in Figure 2. Thus it seems that the second OPCF hydrogen plate was not provided with sufficient hydrogen for two cells, i.e. cell3 and cell4. This issue could be solved by considering two hydrogen supply ports from the both sides of the stack. Additionally, the middle OPCF air plate provides air for two cells, i.e. cell2 and cell3, and has the same thickness as the other two air plates which each serve only one cell. This could reduce the amount of oxygen delivered to internal cells including cell2 and cells3 and lower their output comparing to the other cells. One possible solution for this design problem could be to increase the thickness of the middle OPCF air plate to allow a greater amount of air reaching the internal cells. Cell3 shows the lower

performance among the other cells and this is due to limited amount of hydrogen and air arrived to its anode and cathode sides as described above.

4. Conclusion

In this paper, air-breathing PEM (ABPEM) fuel cells with OPCF material as flow plate material were designed, developed and tested. The developed ABPEM fuel cell, using OPCF as flow plate, has showed better performance than that which uses conventional flow plate due to the capability of OPCF to provide better water management and better distribution of the hydrogen over the catalyst layer.

The effect of the cathode design on the performance of PEM fuel cells was experimentally examined. It was found that the pressurised-air PEM (PAPEM) fuel cell exhibited better performance than the ABPEM fuel cell. This was attributed to the effect of oxidant humidity where the humidity of air used for the PAPEM fuel cell was higher than that absorbed by the ABPEM and thus the ionic conductivity of the membrane was better in PAPEM fuel cell.

Additionally, the ABPEM fuel cell was found to have water management problems due to fact that the free convection was unable to remove the produced water easily and thus the mass transport losses were higher in ABPEM fuel cell type.

To solve the water management issue, a PTFE coating was used on OPCF flow plates. The suitability of such a coating for OPCF in PEM fuel cell application was evaluated via electrochemical polarisation and contact angle measurements. The results showed that the PTFE coating improved the ex-situ and in-situ performance of OPCF in PEM fuel cell environment.

Finally, the OPCF was used to construct a ABPEM fuel cell stack. The performance of this stack was investigated experimentally and the main design problems and potential solutions were discussed. Despite the minor design problems, the innovative fuel cell stack developed in this study has lower weight and less design complexity than the traditional stack.

In summary, the fuel cell design proposed in this paper is significantly different from conventional PEM fuel cell designs and has reduced weight and size which make it very attractive for powering the portable products such as phones, tablets and laptops.

Acknowledgement

The authors would like to thank Enterprise Ireland for funding this work under grant CF20133023.

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Figure 1: 3D CAD model of ABPEM single fuel cell

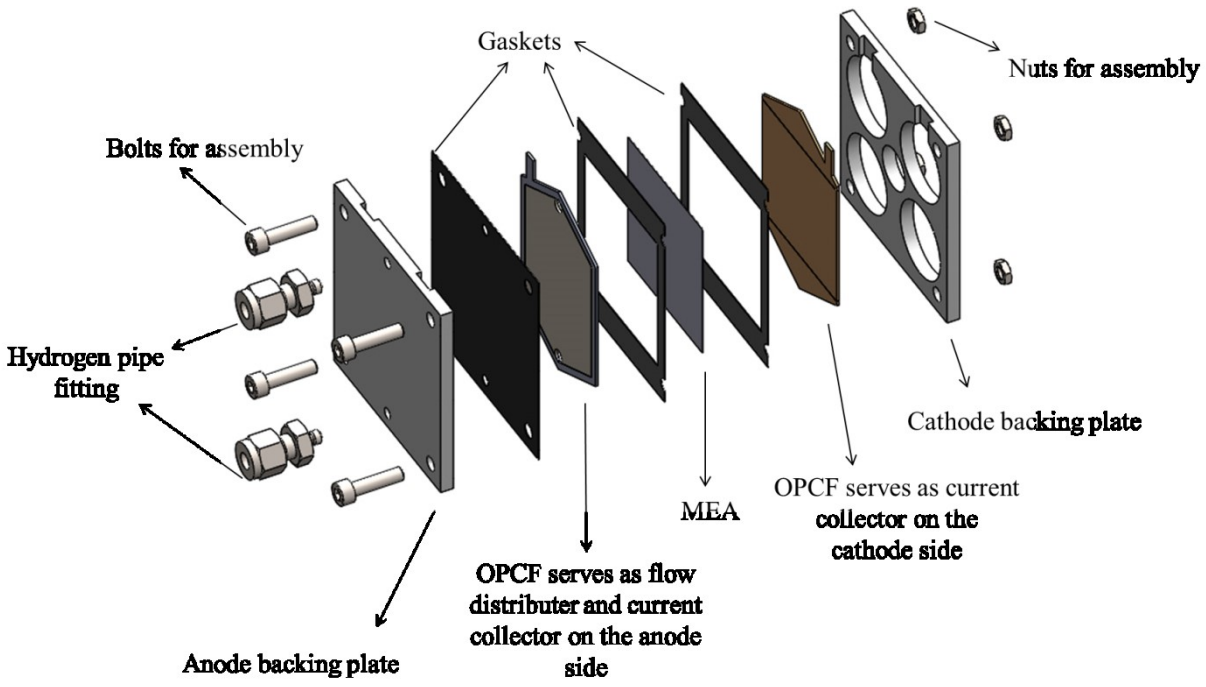
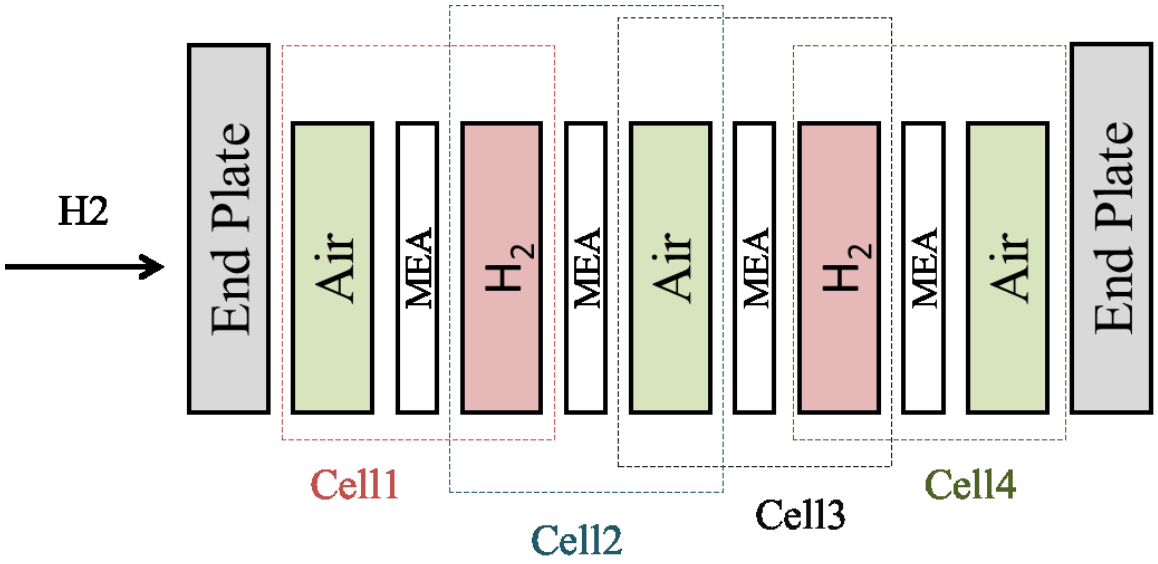
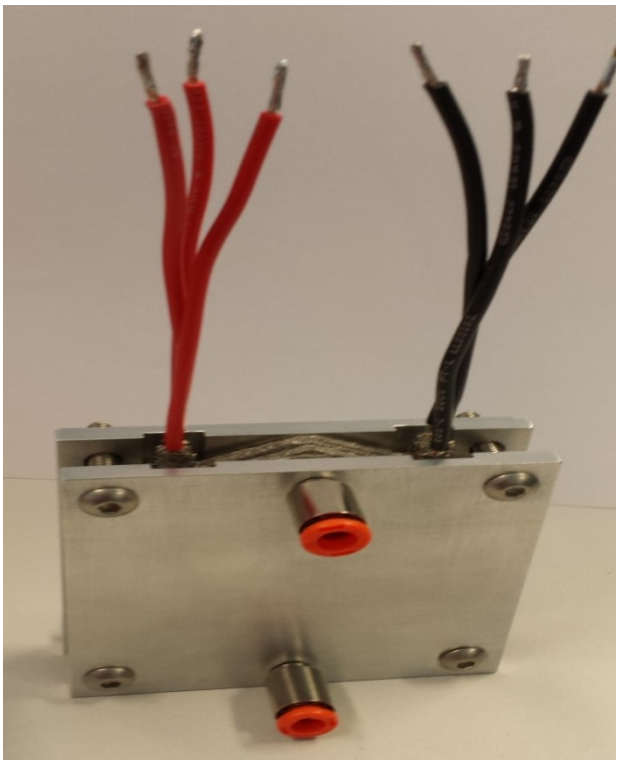


Figure 2: (a) Schematic of ABPEM stack- (b) ABPEM stack prototype



(a)



(b)

Figure 3: PEM fuel cell test setup

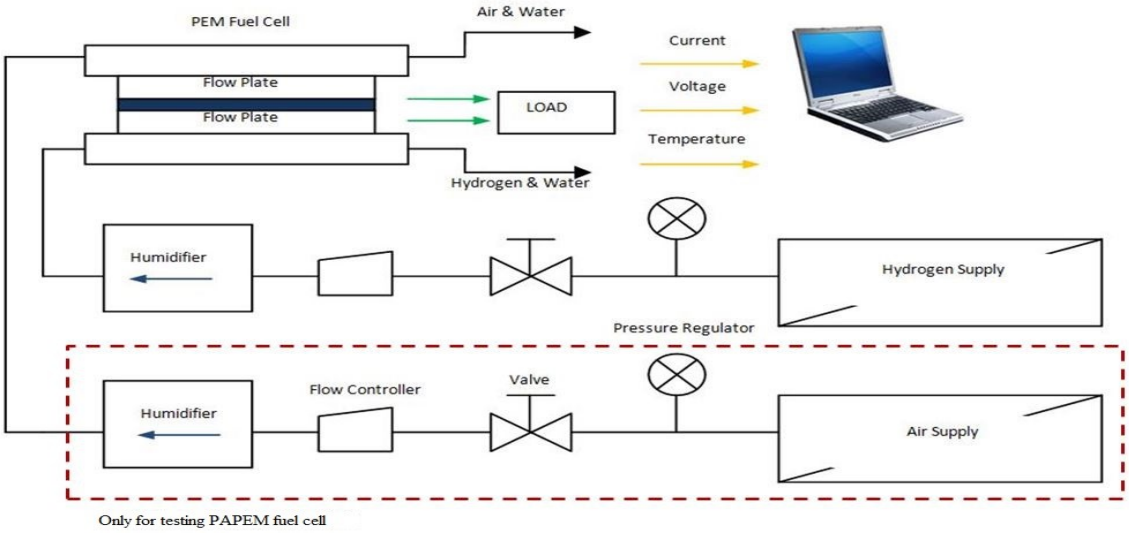


Figure 4 : Polarisation curve comparison for ABPEM fuel cell with OPCF and convention flow distributor.

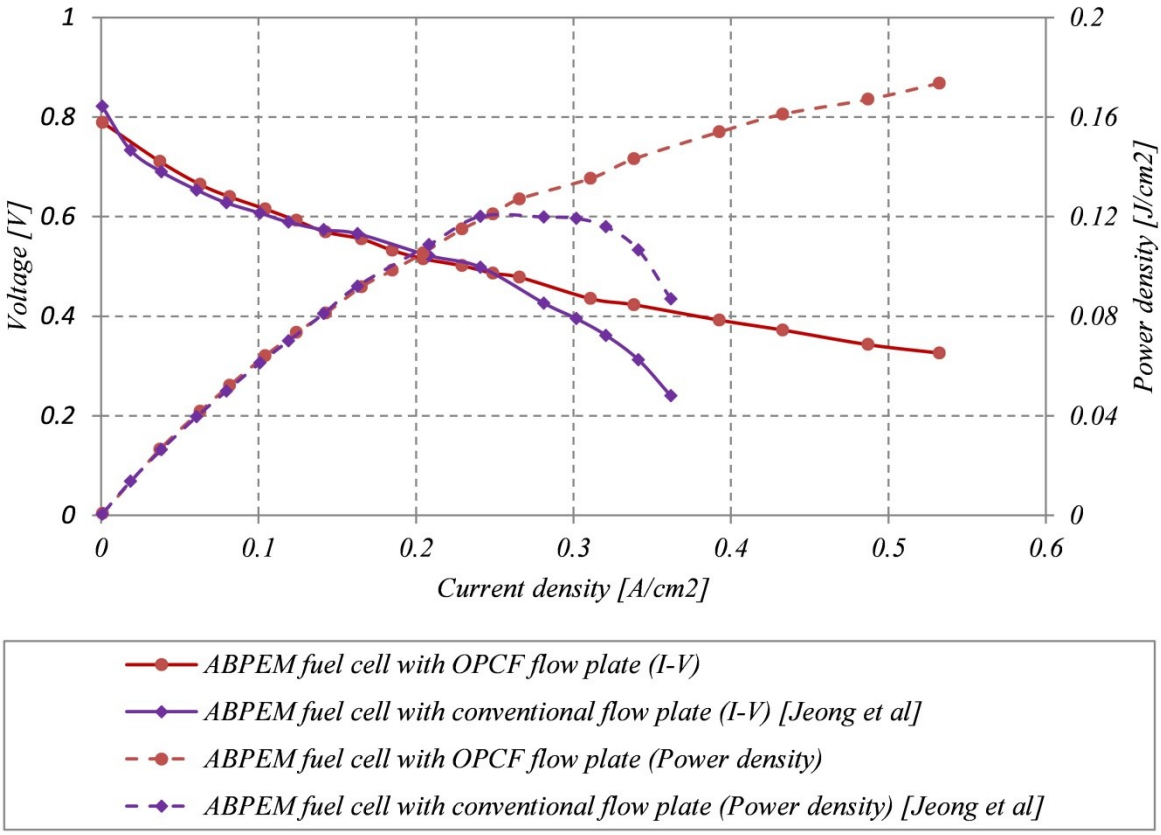


Figure 5: Polarisation curve comparison for ABPEM and PAPEM fuel cells.

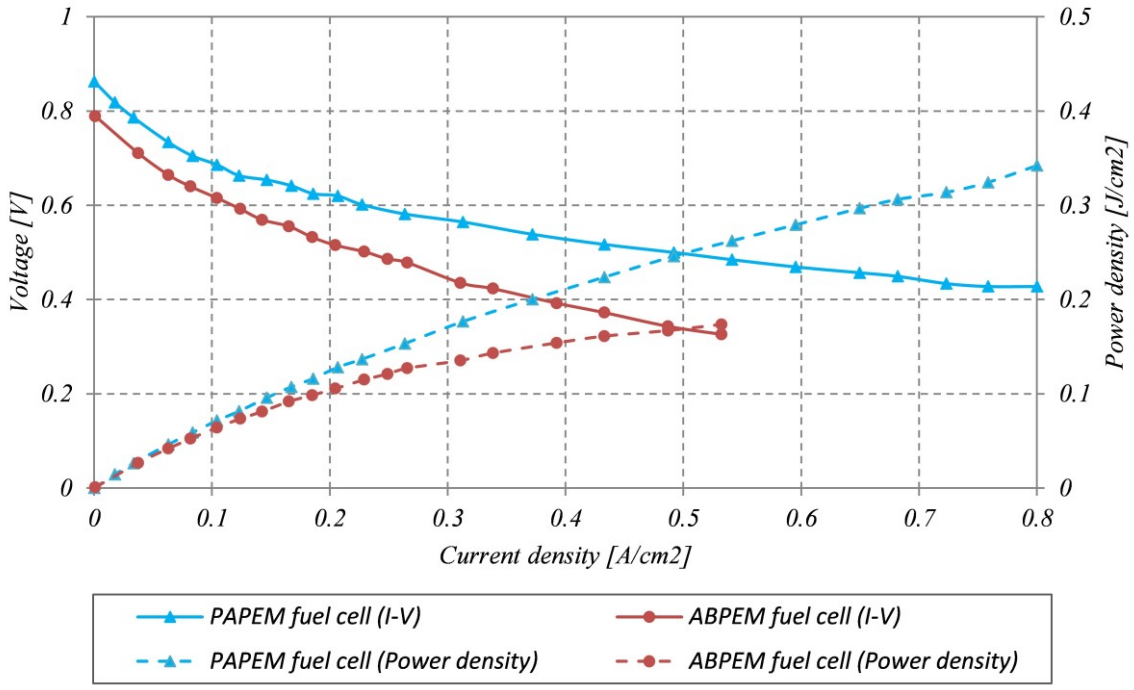


Figure 6: Polarisation curve comparison for ABPEM fuel cell with and without fan assistance.

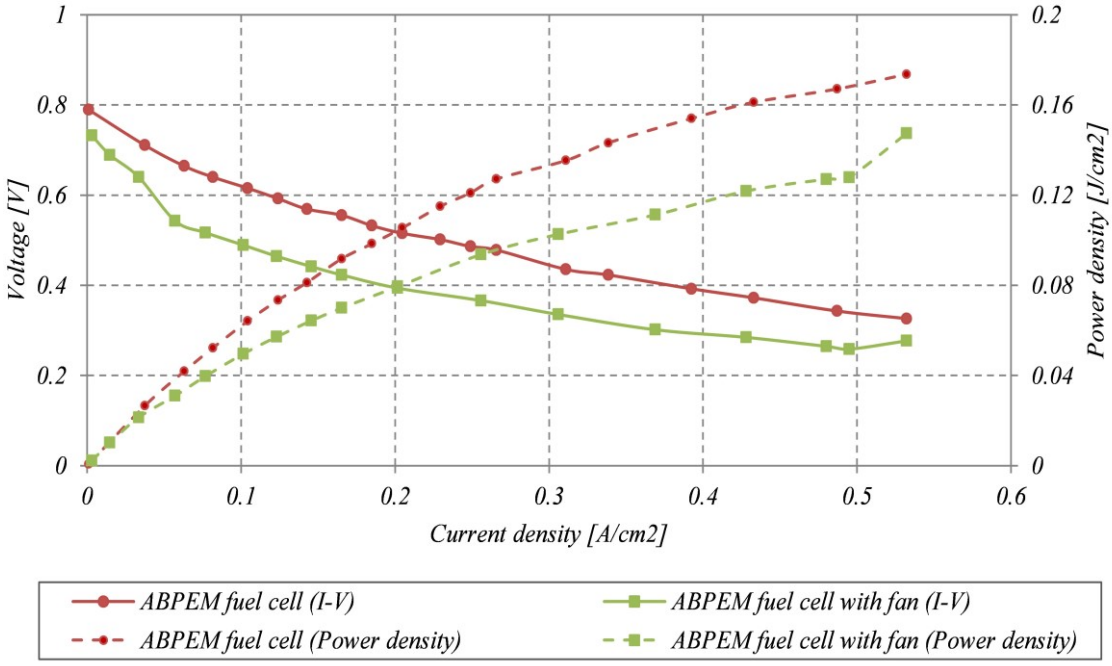
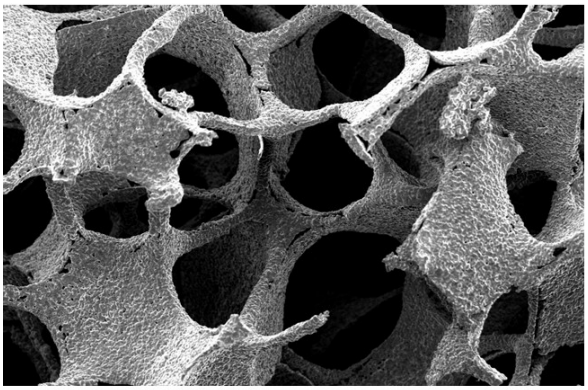
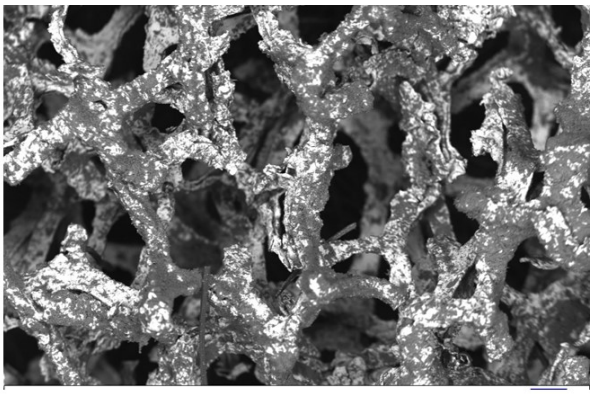


Figure 7: Topographical view of coated and uncoated nickel foam



Uncoated OPCF



PTFE coated OPCF

Figure 8: Water contact angels of coated and uncoated OPCF

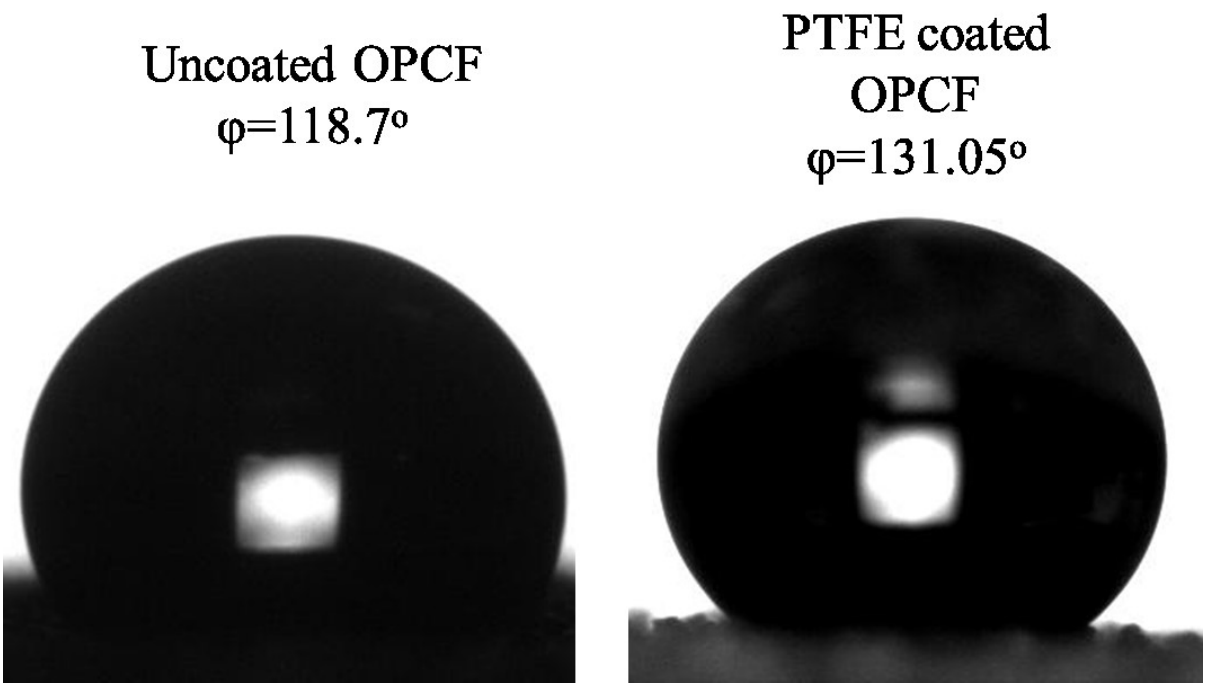


Figure 9: Potentiodynamic polarisation curves of PTFE coated and uncoated OPCF

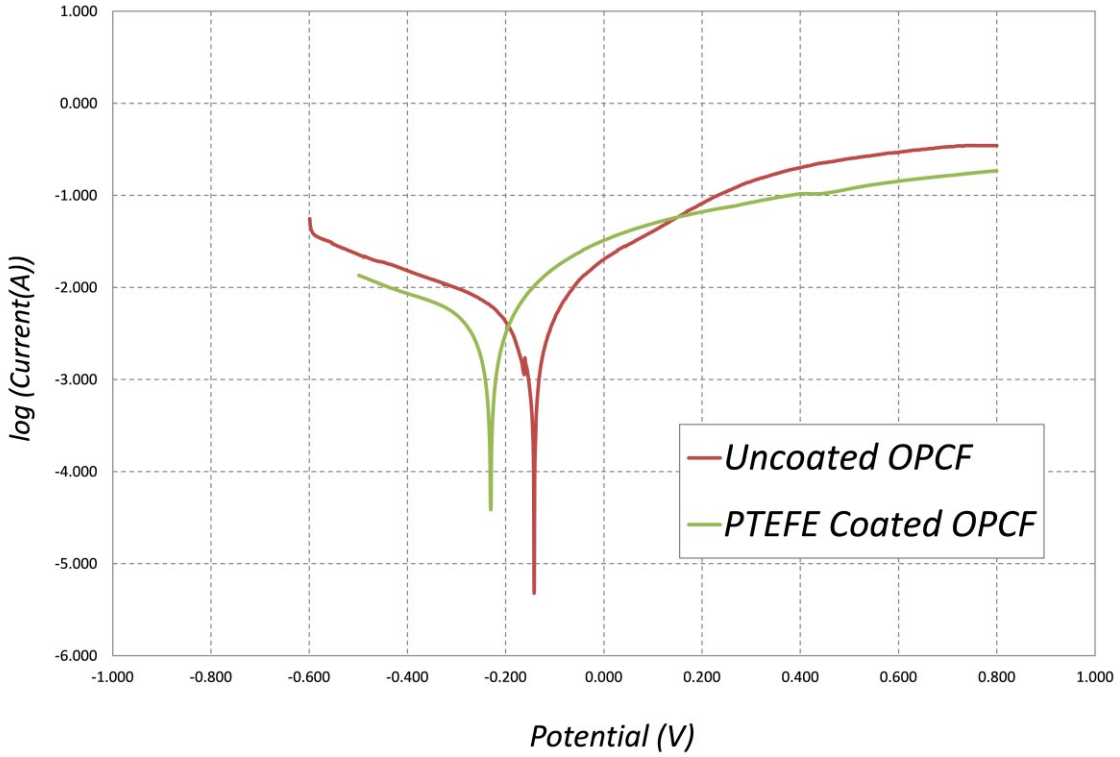


Figure 10: Polarisation curve comparison for ABPEM fuel cell with coated and uncoated OPCF

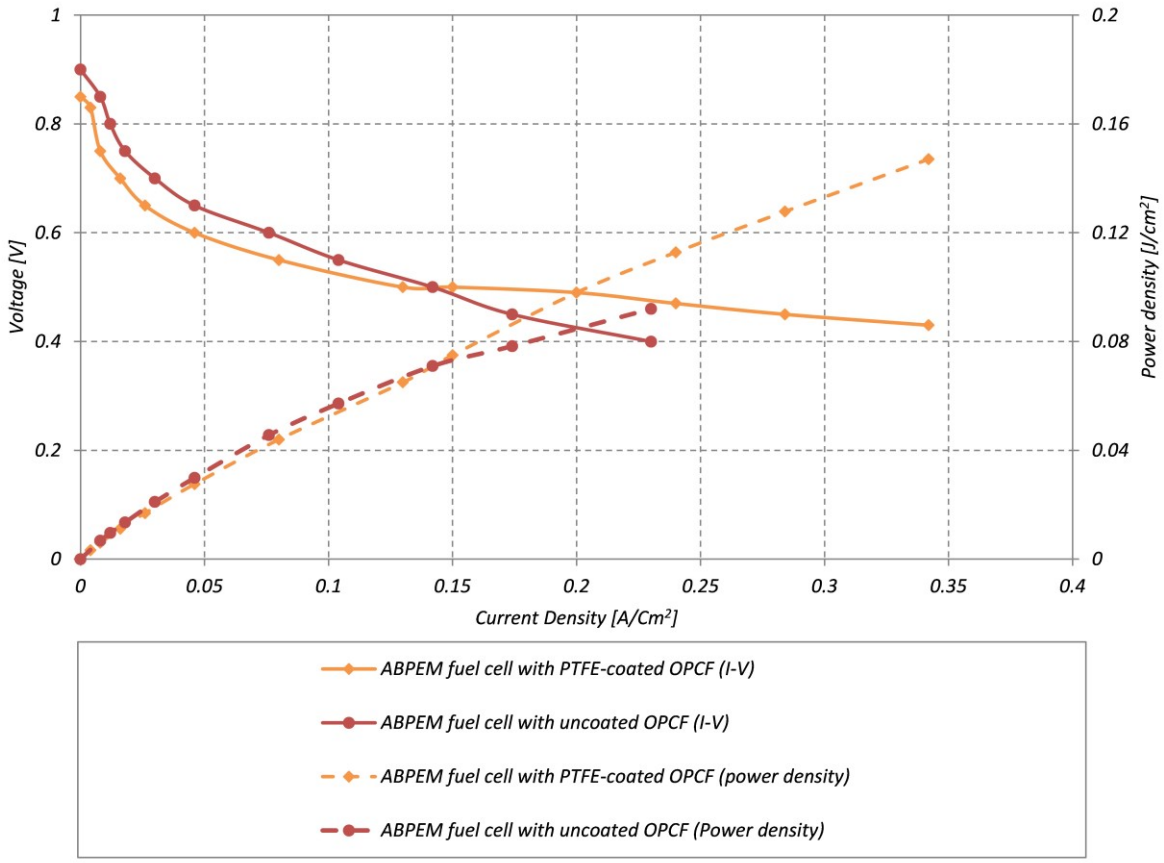


Figure 11: Performance of different cells within the ABPEM fuel cell stack

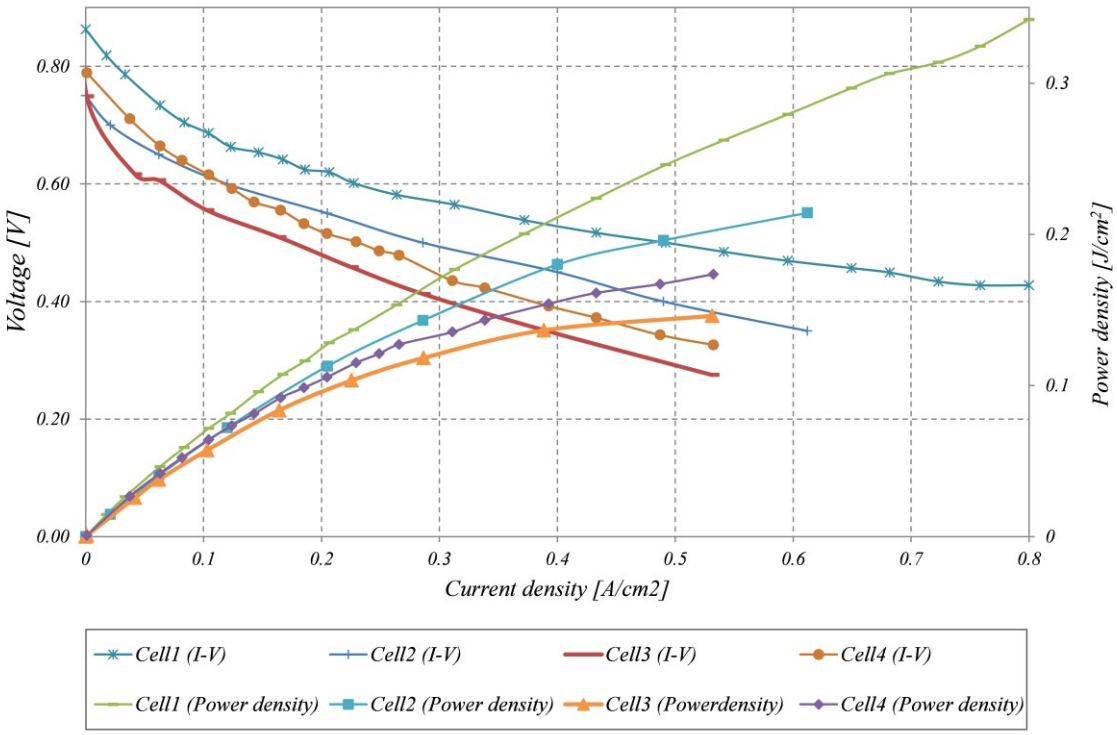


Table 1: Material properties of the fuel cell component

Fuel cell component	Material	Properties
Backing Plate	Aluminium	• Area 7x7 (cm×cm)
MEA	Nafion 212	• Active area: 5×5 (cm×cm), • Catalyst loading: 0.4mg/cm2 Pt/C • GDL: Sigracet SGL 24BC, 0.55g.cm-3 Bulk density.
Flow plate/Current collector	Nickel open cellular foam	• 24 Pores/cm • Thickness: 1 (mm)
Gaskets	Silicon	• Thickness: 0.8 (mm)